Transverse Spin: HERMES Results and Future Plans

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Results from the HERMES experiment are presented on single-spin asymmetries in semi-inclusive hadron production from longitudinally polarized targets. The data are compared with a number of theoretical calculations which relate the azimuthal dependence of the asymmetries to the transversity structure function $h_1(x)$.

1. TRANSVERSITY AND FRIENDS

It has come to light that a complete description of the quark distributions in the proton at leading twist requires not only the structure functions $f_1(x)$ and $g_1(x)$, but also the transversity distribution $h_1(x)$. This new structure function represents the degree to which the quarks are polarized along the proton's spin direction when the proton is polarized transversely to the virtual photon. The unique properties of $h_1(x)$ were beautifully presented by R. Jaffe at this conference. The majority of this report is devoted to recent data sensitive to $h_1(x)$.

However, one may place transversity in a larger context. In 1996, Mulders and Tangerman performed a complete tree-level analysis of the semi-inclusive deep-inelastic scattering (SIDIS) cross-section, taking into consideration all measurable spin-degrees of freedom in the initial and final state [1]. Their work identified a series of 8 structure functions of the proton at leading twist, along with an analogous set of 8 fragmentation functions. These functions are illustrated graphically in Fig. 1a. In each picture, the virtual photon probe is assumed to be incident from the left, the large and small circles represent hadrons and quarks respectively, and the arrows indicate their spin directions. The notation for the fragmentation functions is obtained by replacing the letters f, g, and h with D, G, and H respectively.

Each of these functions describes qualitatively different information about hadronic structure and formation. The functions $f_1(x)$, $g_1(x)$, and $h_1(x)$ are the only ones which survive on integration over transverse momentum k_T. (The same is true of the analogous fragmentation functions.) The other functions are all implicitly dependent on intrinsic quark transverse motion, which is necessarily related to the unknown orbital angular momentum of quarks in the nucleon. New data are providing first glimpses of several functions in this table, and much more can be expected in the near future.

The Mulders decomposition of the cross-section reveals that experiments may access these new structure and fragmentation functions by measuring *azimuthal moments* in spin-dependent SIDIS. Fig. 1(b) illustrates the HERMES definition of ϕ, the azimuthal angle of the measured final-state hadron, around the virtual photon direction, and relative
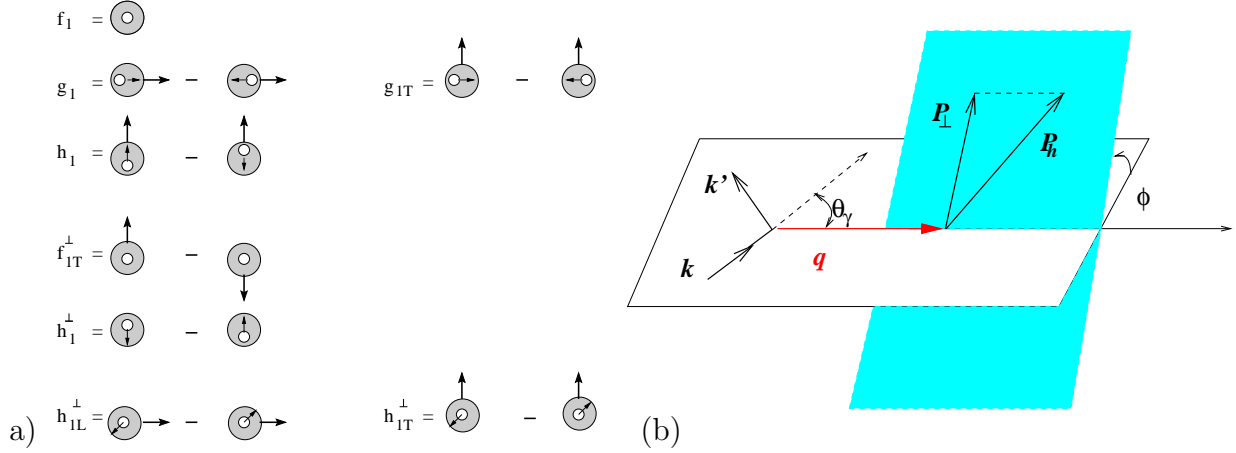
Figure 1. (a) Summary of the classification scheme of [1] for leading-twist distribution functions. (b) Diagram of SIDIS kinematics.

to the lepton scattering plane. Specifically one must perform an azimuthal decomposition of various cross-section terms $d\sigma_{\mathrm{ABC}}$, where A, B, and C represent the spin-polarization of the lepton beam, proton target, and final-state hadron respectively. These subscripts take the values L, T, and U, denoting longitudinal, transverse, and no polarization. The spin of the final-state hadron can usually be accessed only by Λ-production measurements: the weak decay $\Lambda \to p\pi^-$ allows the hyperon's spin to be determined from the angular distribution of its decay products.

2. THE HERMES EXPERIMENT

The HERMES experiment has been taking data at the HERA accelerator in Hamburg, Germany since 1995. HERMES scatters longitudinally polarized electron and positron beams of 27.6 GeV from polarized gas targets internal to the beam pipe. Pure atomic H, D, and ^{3}He have been used (as well as a variety of unpolarized nuclear targets). Featuring polarized beams and targets, and an open-geometry spectrometer with good particle identification (PID), HERMES is well suited to a study of the spin-dependent azimuthal moments of the SIDIS cross-section. The PID capabilities of the experiment were significantly enhanced in 1998 when the threshold Čerenkov detector (used to identify pions above a momentum of 4 GeV) was upgraded to a Ring Imaging system (RICH). This new detector provides full separation between charged pions, kaons, and protons over essentially the entire momentum range of the experiment.

In September 2000 HERMES completed its first phase of data taking, using longitudinally-polarized targets. The 1998-2000 period was particularly successful, yielding a very large data set (> 8 million DIS events) from polarized deuterium. HERMES is now entering its second running phase which will continue until 2006. A cornerstone of this period will be measurements from transversely-polarized targets, with the specific goal of exploring the transversity structure function. Prospects for Run 2 were described in the talk of K. Rith at this conference.

3. HERMES MEASUREMENTS OF $A_{\mathrm{UL}}(\phi)$

HERMES has measured the azimuthal distribution of charged [4] and neutral [5] pions in the scattering of "unpolarized" positrons from a longitudinally-polarized hydrogen target. (As the HERA beam is always polarized, an "unpolarized" sample was achieved by the helicity-balancing of data collected with opposite beam polarization.) The measured quantity is the following single-spin asymmetry (SSA):

$$A_{\mathrm{UL}}(\phi) = \frac{1}{P_T} \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}. \tag{1}$$

Here P_T is the target polarization and ϕ is the azimuthal angle of the pion described above. N^+ and N^- represent the pion yields in each of the two target spin orientations, with the superscript indicating the helicity of the target in the reaction's center-of-mass frame (*i.e.* N^+ is collected when the target spin is antiparallel to the lepton beam momentum in the lab frame). This choice is motivated by the familiar definition of the double-spin asymmetry A_{LL}. It is also important to note that the HERMES definition of ϕ is *not* the same as that of the "Collins angle" ϕ_C which appears in a number of publications.

The measured asymmetries show a significant $\sin\phi$ moment in the case of π^+ and π^0 production, while no ϕ-dependence is seen in π^- production. The $\sin 2\phi$ moments of the asymmetries were also analyzed and found to be consistent with zero in all cases. The mean Q^2 of these measurements is around 1.6 GeV^2.

At "zeroth-order" in complexity, the asymmetry moment $A_{\mathrm{UL}}^{\sin\phi}$ (also termed analyzing power) is related to the product of transversity $h_1(x)$ and the Collins fragmentation function $H_1^\perp(z)$. This latter function provides a "polarimeter" for initial-state quark polarization: it correlates the transverse spin of the struck quark with the angular distribution of hadrons in the jet it generates. Fig. 2 shows the dependence of $A_{\mathrm{UL}}^{\sin\phi}$ on the Bjorken scaling variable x, the energy fraction $z \equiv E_h/\nu$ of the pion, and its transverse momentum p_T relative to the virtual photon direction. The dependences match the qualitative predictions of Collins [2] that the effect should peak in the valence region $x \simeq 0.3$, rise with p_T up to a maximum at some hadronic scale $0.3 - 0.9$ GeV, and be larger for π^+ than π^- production.

The reason for this last expectation can be shown by a simple calculation. It is reasonable to guess that the transverse quark polarization ($\delta q \equiv h_1^q$) is similar to the longitudinal quark polarization ($\Delta q \equiv g_1^q$) in the sense $\delta d/\delta u \approx \Delta d/\Delta u \approx -1/2$. One may also estimate that the favoured and disfavoured Collins fragmentation functions have a similar ratio as in the unpolarized case ($r \equiv D_d^{\pi^+}/D_u^{\pi^+} \approx (1-z)/(1+z) \approx 1/3$). One then arrives at these simple estimates:

$$A_p^{\pi^+} \approx \frac{4\,\delta u + r\,\delta d}{4\,u + r\,d} \approx \frac{\delta u}{u}, \qquad A_p^{\pi^0} \approx \frac{4\,\delta u + \delta d}{4\,u + d} \lesssim \frac{\delta u}{u}, \qquad A_p^{\pi^-} \approx \frac{4\,r\,\delta u + \delta d}{4\,r\,u + d} \approx 0 \tag{2}$$

The expectation of similar π^+ and π^0 asymmetries is also supported by the data.

HERMES has recently completed an analysis of A_{UL} from the deuterium-target data collected in the years 1998 to 2000. In Fig. 3 preliminary results are presented for the analyzing power $A_{\mathrm{UL}}^{\sin\phi}$ for charged pion production. A simple calculation of the type given in Eq. 2 leads to the expectation that $A_{\mathrm{UL}}^{\sin\phi}$ from deuterium should be roughly
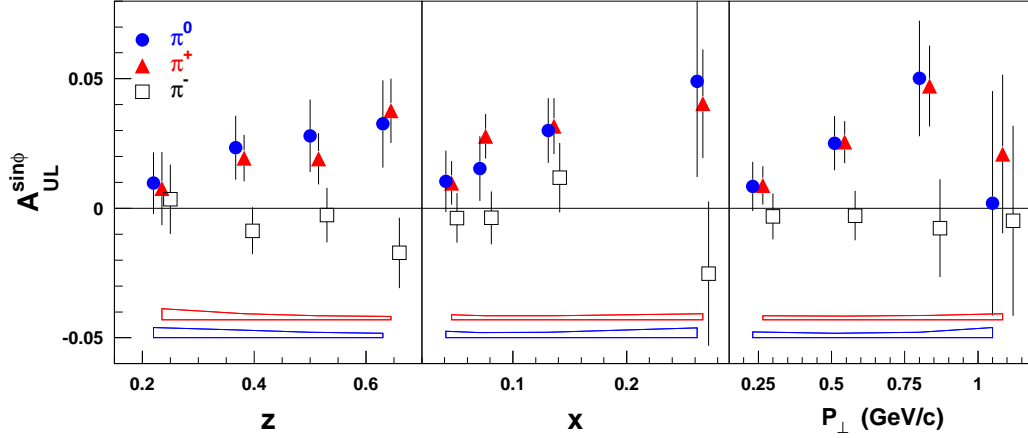
Figure 2. Kinematic dependences of $A_{\mathrm{UL}}^{\sin\phi}$ measured from a hydrogen target [4,5].

the same for π^+, π^-, and π^0 production, and around half as large as for π^+ production from hydrogen. These qualitative expectations are indeed borne out by the data. Spin-azimuthal asymmetries for charged kaon production have also been measured for the first time, as shown in the right-hand panel of Fig. 3.
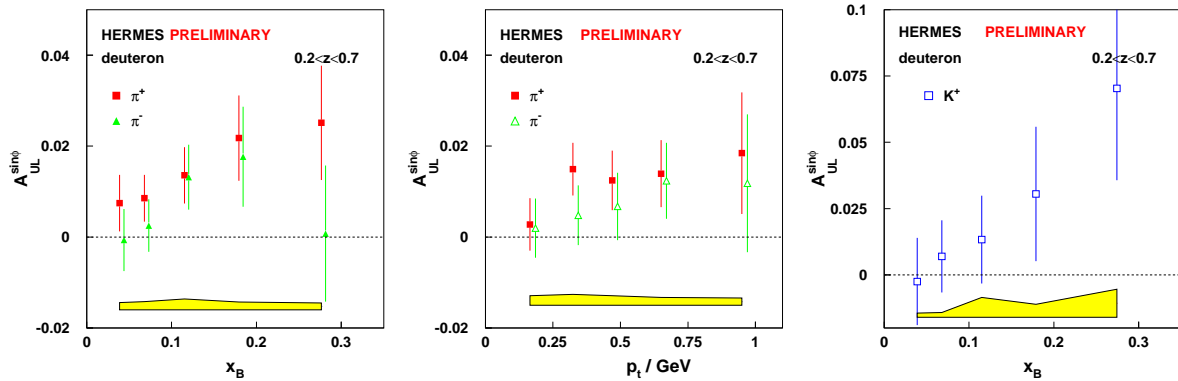

Figure 3. HERMES preliminary results on the analyzing power $A_{\mathrm{UL}}^{\sin\phi}$ for charged pion and kaon production from a deuterium target.

3.1. Modelling $A_{\mathrm{UL}}(\phi)$

For a more sophisticated interpretation of the data, one must consider in detail which terms in the SIDIS cross-section of ref. [1] contribute to the $A_{\mathrm{UL}}(\phi)$ asymmetry. It is essential to realize that "longitudinal" and "transverse" target polarization have different meanings in experimental and theoretical contexts. In experimental papers, a longitudinal target is polarized along the *lepton beam* direction, but in theoretical contexts the relevant axis is the *virtual photon* direction. To distinguish the two, we use the notation A_{ABC}^{w} for moments w of asymmetries in the experimental convention, and the notation $\langle w \rangle_{\mathrm{ABC}}$ of ref. [1] to denote moments of the cross-section in the theoretical convention. The

HERMES measurement of $A_{\mathrm{UL}}^{\sin\phi}$ can thus be expressed as follows:

$$A_{\mathrm{UL}}^{\sin\phi} = \frac{S_L \langle \sin\phi \rangle_{\mathrm{UL}} + S_T \langle \sin\phi \rangle_{\mathrm{UT}}}{S \langle 1 \rangle_{\mathrm{UU}}}. \qquad (3)$$

Here S_L and S_T represent the longitudinal and transverse projections of the target polarization S onto the virtual photon direction. At HERMES $S_L/S \approx 1$, and $S_T/S \approx 1/Q$.

The full theoretical decomposition of $A_{\mathrm{UL}}^{\sin\phi}$ and $A_{\mathrm{UL}}^{\sin 2\phi}$ involves a number of functions at both leading and higher twist:

$$\langle 1 \rangle_{\mathrm{UU}} \sim f_1(x)\, D_1(z), \qquad \langle \sin\phi \rangle_{\mathrm{UT}} \sim h_1(x)\, H_1^{\perp(1)}(z), \qquad \langle \sin 2\phi \rangle_{\mathrm{UL}} \sim h_{1L}^{\perp(1)}(x)\, H_1^{\perp(1)}(z),$$

$$\langle \sin\phi \rangle_{\mathrm{UL}} \sim \frac{1}{Q}[h_{1L}^{\perp(1)}(x)\, H_1^{\perp(1)}(z) \;\oplus\; \tilde{h}_L(x)\, H_1^{\perp(1)}(z) \;\oplus\; h_{1L}^{\perp(1)}(x)\, \tilde{H}] \qquad (4)$$

All kinematic prefactors have been suppressed in these expressions for brevity. The superscript (1) appearing on several of the functions denotes a k_T^2-weighted integral over transverse momentum.

The $\langle \sin\phi \rangle_{\mathrm{UT}}$ moment is directly proportional to the product of transversity and the Collins function. However the present HERMES measurement is most directly related to $\langle \sin\phi \rangle_{\mathrm{UL}}$, which is much more complex: it is sub-leading in Q, and contains the interaction-dependent twist-3 functions $\tilde{h}_L$ and $\tilde{H}$. In addition the as-yet-unknown leading-twist distribution function $h_{1L}^{\perp}(x)$ makes an appearance (see Fig. 1).

It is necessary to make a few assumptions in order to proceed with modelling of the asymmetry. The unknown functions $\tilde{h}_L$ and $h_{1L}^{\perp}$ are not unrelated; from Lorentz and rotational invariance one may derive the relation

$$h_{1L}^{\perp(1)}(x) = x^2 \int_x^1 \frac{dy}{y^2} \left[-h_1(y) + \tilde{h}_L(y) + \frac{m_q}{M_p} \frac{g_1(y)}{y} \right]. \qquad (5)$$

Two approximations are commonly made in the literature. The first is the "reduced twist-3 approximation", which assumes that all twist-3 terms that are interaction-dependent or suppressed by the quark-mass m_q are zero. The second choice is to set the distribution function $h_{1L}^{\perp}$ to zero. This last option is motivated by the HERMES measurement of $A_{\mathrm{UL}}^{\sin 2\phi} \approx 0$, as $A_{\mathrm{UL}}^{\sin 2\phi}$ is proportional to $h_{1L}^{\perp}$ (Eq. 4). With one of the functions $h_{1L}^{\perp}$ or $\tilde{h}_L$ set to zero, the other can be calculated using Eq. 5 and a model for transversity.

The Collins fragmentation function is also unknown. Its kinematic shape is typically taken from the heuristic parametrization of ref. [2],

$$\frac{H_1^{\perp}(z, k_T)}{D_1(z)} = \eta \frac{M_C M_h |k_T|}{M_C^2 + k_T^2}, \qquad (6)$$

with some normalization constant η and hadronic scale $M_C \approx 2\, m_\pi - M_p$. These parameters may be constrained using hadron-production data from DELPHI: a quark and antiquark produced from Z^0 decay carry small but highly-correlated transverse polarizations. A pioneering analysis of these data [6] has yielded the estimate $|H_1^{\perp}/D_1| = 6.3 \pm 1.7$ %. (Very recently, the value has been amended to 12.5 ± 1.4 % [7].) Unfortunately this result is an average value integrated over a rather poorly defined interval in z. Nevertheless, it provides an important indication of the size of the Collins function, and one which is independent of uncertainties in the distribution function sector. As presented by A. Ogawa at this workshop, high statistics data from the BELLE experiment will soon be analyzed in a similar fashion to yield much more precise results on $H_1^{\perp}$.

3.2. Comparison with Model Calculations

A variety of theoretical calculations have been performed to address the HERMES measurements of $A_{\mathrm{UL}}(\phi)$.

The work of ref. [8] attempts to explain the data with a range of simple ansätze. In Fig. 4(a) and (b), the solid curves correspond to the assumption that $h_{1L}^{\perp} = 0$, while the dashed curves correspond to the "reduced twist-3" approximation $\tilde{h}_L = 0$. In each case, two guesses are made for the magnitude of the transversity distribution: $h_1 = g_1$, and saturation of the Soffer bound $h_1 = (f_1 + g_1)/2$. The calculations show that the majority of the asymmetry (around 75%) originates from the subleading term $\langle \sin \phi \rangle_{\mathrm{UL}}$ associated with the longitudinal component of the target polarization, with only a quarter coming from the leading twist term $\langle \sin \phi \rangle_{\mathrm{UT}}$. This fact is reflected in the curves: $A_{\mathrm{UL}}^{\sin \phi}$ is more sensitive to the ansatz made for the higher-twist functions (solid vs dashed curves) than to the magnitude of h_1 itself. Also, the data appear to indicate that the interaction-dependent twist-3 function $\tilde{h}_L$ cannot be ignored, while the unknown twist-2 function $h_{1L}^{\perp}$ is likely of small magnitude.
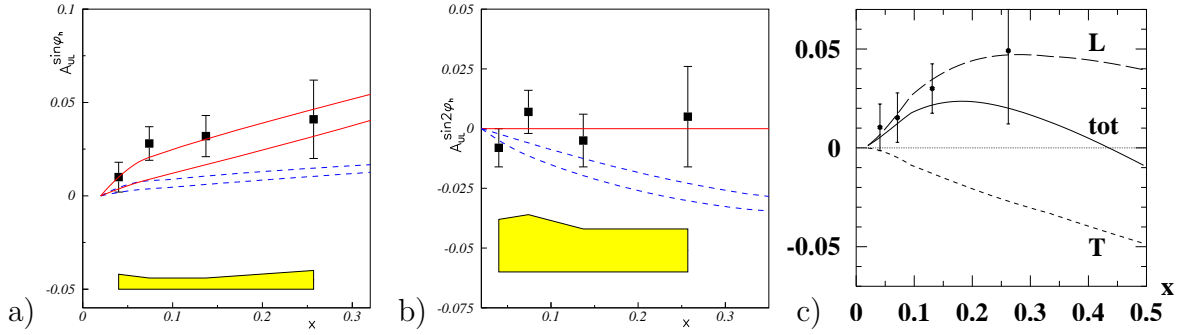

Figure 4. Calculations from ref. [8] of (a) $A_{\mathrm{UL}}^{\sin \phi}$ and (b) $A_{\mathrm{UL}}^{\sin 2\phi}$ for π^+ production from a hydrogen target. Panel (c) shows the χQSM calculation from ref. [7] of $A_{\mathrm{UL}}^{\sin \phi}$ for π^0 production; the L and T curves show the contributions from the longitudinal and transverse components of the target polarization.

In ref. [9], $h_1(x)$ has been calculated directly in the Chiral-Quark Soliton Model (χQSM) and used to estimate the asymmetry moments $A_{\mathrm{UL}}^{\sin \phi}$ and $A_{\mathrm{UL}}^{\sin 2\phi}$ in the reduced twist-3 approximation $\tilde{h}_L = 0$. The calculations agree with the HERMES measurements for both charged and neutral pions, and also indicate that the longitudinal term $\langle \sin \phi \rangle_{\mathrm{UL}}$ makes the dominant contribution to the effect (see Fig. 4(c) for π^0 production, taken from the corrected analysis of ref. [7]). A second χQSM calculation can be found in ref. [10]. In this work, *all* distribution functions involved in the asymmetries were calculated: h_1, $\tilde{h}_L$, and $h_{1L}^{\perp}$. The higher-twist function $\tilde{h}_L$ is found to be of significant magnitude, especially in the region $x < 0.2$, while the unknown leading-twist distribution function $h_{1L}^{\perp}$ is predicted to be small but non-zero. The calculations for $A_{\mathrm{UL}}^{\sin \phi}$ and $A_{\mathrm{UL}}^{\sin 2\phi}$ are again in agreement with the HERMES data, within experimental accuracy.

Calculations in other models have been performed [11] and obtain reasonable agreement with the measurements. All calculations agree that $A_{\mathrm{UL}}^{\sin \phi}$ is dominated by higher-twist

effects, due to the longitudinal target polarization. For a better understanding of transversity, the next step is clear: high precision SIDIS data on a transversely-polarized target are required.

4. GLOBAL ANALYSIS OF SINGLE SPIN ASYMMETRY DATA

Earlier data from the Fermilab E704 experiment, from DELPHI, and from SMC at CERN are also potentially related to transversity. It is worthwhile to consider whether a consistent picture has emerged from theoretical analyses of these data sets.

4.1. E704 and the Sivers Function

About 10 years ago, the Fermilab E704 experiment measured a large analyzing power A_N in the inclusive production of pions from a transversely polarized proton beam of 200 GeV and an unpolarized target [12]. Unexpectedly, positive and neutral pions displayed a pronounced tendency to be produced to "beam-left" (when looking downstream with the beam polarization pointing upwards). Negative pions showed a similar analyzing power, but in the opposite "beam-right" direction.

The observables A_N and $A_{\rm UL}^{\sin \phi}$ are odd under the application of naive time reversal, and must arise from the non-perturbative part of the cross-section. In the factorization picture of ref. [1], either a T-odd fragmentation function or a T-odd distribution function must play a role. In the first case, the E704 analyzing power is sensitive to the product of transversity h_1 and the T-odd Collins fragmentation function $H_1^\perp$. The second possibility involves the unknown T-odd distribution function $f_{1T}^\perp(x, k_T)$ first postulated by Sivers [13], together with the familiar unpolarized fragmentation function D_1. Fits performed in the Collins-only [14] and Sivers-only [15] scenarios demonstrate that the E704 data may be described with equal success by either picture.

Considerable discussion occurred at this workshop concerning the nature of the Sivers function $f_{1T}^\perp$. Given the T-even nature of the strong and electromagnetic interactions, any T-odd function must involve an interference of amplitudes [16]. The most obvious way to generate such an interference is via inital- or final-state interactions. Both are possible in a hadronic-beam experiment such as E704. In deep-inelastic scattering with lepton beams, initial state interactions (and so the Sivers mechanism) should be greatly suppressed. It may thus be said that the HERMES measurement of $A_{\rm UL}$ provides the first conclusive evidence that the Collins function and transversity are both non-zero and of significant magnitude.

However, other suggestions exist for the origin of $f_{1T}^\perp$, including contributions from gluonic poles [17] and spin-isospin interactions [18]. Further experimental and theoretical work is needed to determine the magnitude of this function, whether it plays any role in lepton DIS, and whether it exists at all at leading twist. As with all other distribution functions that vanish on integration over transverse momentum, the Sivers function must be related at some level to parton orbital motion. A tantalizing physical interpretation of this function in the context of the E704 asymmetry may be found in ref. [19].

Turning briefly to the fragmentation aspect of these measurements, the existence of the Collins function is deeply interesting in its own right. As it must arise from some interference mechanism, it teaches us that the fragmentation process possesses a large degree of *phase coherence.* Older data on transverse hyperon polarization from high-

energy unpolarized experiments have already provided evidence that this is the case [20]. They are sensitive to the "polarizing" fragmentation function $D_{1T}^\perp(z, k_T)$ which is also T-odd. It is rather surprising that such interference effects persist at high energies, given the large number of amplitudes that must be involved in inclusive or semi-inclusive hadron production.

4.2. Global Analysis of Single-Spin Asymmetries

A tentative, qualitative concensus has begun to emerge among the various analyses of single-spin asymmetry data at high energies. The available data from HERMES, E704, and SMC may all be described by the transversity distribution calculated in the χQSM, a Sivers function of zero, and a Collins function of approximate magnitude $|H_1^\perp/D_1| \approx 7\%$ [9,14]. This apparent concensus is qualitative at best: the uncertainties on the present experimental data and the rather poorly defined z-ranges over which the data are integrated certainly leave room for the existence of the Sivers function, for example. Also, a pair of sign errors was recently uncovered in the analyses of the HERMES and DELPHI data [7]. The updated estimates for the Collins function are larger than before: $|H_1^\perp/D_1| = 12.5 \pm 1.4$ % from the DELPHI data and $|H_1^\perp/D_1| = 13.8 \pm 2.8$ % from the HERMES data. It is presently unclear to what degree such sign errors affect other theoretical analyses of transversity-related measurements.

5. FUTURE MEASUREMENTS OF TRANSVERSITY

It is clear from Eq. 4 that the most direct access to transversity in SIDIS lies in measurements with transversely polarized targets. A precise measurement of $A_{\mathrm{UT}}(\phi)$, sensitive at leading twist to the product of $h_1(x)$ and $H_1^\perp(z)$, will form a cornerstone of HERMES Run 2. Besides $A_{\mathrm{UT}}(\phi)$, HERMES has considered other observables that may be sensitive to h_1. A promising candidate is the correlation between the transverse polarization of the target and of final-state Λ baryons, described by the spin-transfer fragmentation function $H_1(z)$. If this function is of significant size, Λ polarization can serve as a "polarimeter" for the quark spin distribution in the target. However results from HERMES indicate that the *longitudinal* spin-transfer from struck quark to Λ ($G_1(z)$) is small in DIS at intermediate energies [21]. This likely indicates that the transverse spin transfer will also be small and that Λ polarization will not serve as a useful tactic for future transversity measurements.

It is important to note that the next round of single-spin asymmetry measurements *will* be able to distinguish between the Collins and Sivers mechanisms. The SIDIS cross-section term $d\sigma_{\mathrm{UT}}$ has two contributions according to ref. [1]: a $\sin(\phi_h^l + \phi_S^l)$ moment proportional to $h_1 H_1^\perp$, and a $\sin(\phi_h^l - \phi_S^l)$ moment proportional to $f_{1T}^\perp D_1$. The symbols ϕ_S^l and ϕ_h^l indicate the angle of the target spin and final-state hadron momentum respectively, with respect to the lepton scattering plane. The angular dependence of the Collins term may be understood by realizing that the spin directions of the struck quark (ϕ_q^l) and final-state quark ($\phi_{q'}^l$) are related by $\phi_q^l = \pi - \phi_{q'}^l$ [2]: when the virtual photon is absorbed by the struck quark, the component of the quark's spin parallel to the lepton scattering plane is flipped, while the perpendicular component is left unaffected. The Collins fragmentation function, which correlates hadron direction with the spin of the primary quark, produces a $\sin(\phi_h^l - \phi_{q'}^l)$ behavior. Transversity relates ϕ_q^l to ϕ_S^l, giving a net $\sin(\phi_h^l + \phi_S^l)$ dependence

in the cross section. The Sivers function, on the other hand, correlates quark transverse (orbital) motion with target spin. This motion is transferred directly to the final-state hadrons by D_1, giving a net $\sin(\phi_h^l - \phi_S^l)$ behavior.

Current HERMES data cannot distinguish between the two: ϕ_S^l is always zero or π for a target polarized longitudinally in the laboratory frame. Similarly, the E704 data could not distinguish between the moments as their experimental apparatus did not permit a measurement of the jet axis around which the pions were produced. But forthcoming HERMES data with a transversely-polarized target will permit the independent variation of the target spin angle ϕ_S^l and the hadron angle ϕ_h^l.

In conclusion, data collected in recent years have provided a first glimpse of the transversity distribution and the Collins fragmentation function. The data are still of modest precision, but they "make sense": the measurements can be described by a variety of theoretical models and resonable assumptions. This baseline understanding has provided clear guidance on which measurements to perform next. The upcoming round of results from HERMES, COMPASS, RHIC-spin, and BELLE will provide much more precise information on transversity and on other new structure and fragmentation functions.

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